# PROPAGATION OF THE PHASE OF SOLAR MODULATION

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ABSTRACT

The phase of the 11-year galactic cosmic-ray variation, due to a varying rate of emission of long-lived, propagating regions of enhanced scattering, travels faster than the scattering regions themselves. The radial speed of the 11-year phase in the quasi-steady, force-field approximation is exactly twice the speed of the individual, episodic decreases. A time-dependent, numerical solution for 1-GeV protons at 1 and 30 AU gives a phase speed which is 1.85 times the propagation speed of the individual decreases.

1. Introduction. Sudden decreases in cosmic-ray intensity have been observed to propagate outward in the ecliptic plane at about 400-500 km/s, the solar wind speed [McDonald et. al., 1981; McKibben et. al., 1982; Van Allen, 1979; Venkatesan et. al., 1984; see review by Burlaga, 1983]. These decreases are related to regions of enhanced magnetic field strength and turbulence, which strongly suggests enhanced reflection and scattering of cosmic rays. Although these regions are very prominent near the ecliptic plane, it is not clear that all modulation can be ascribed to them. We do not know how their effects extend out of the ecliptic, nor how they may modify the expected modulation due to large-scale drift and the neutral sheet [Jokipii & Davila, 1981; Kota & Jokipii, 1982].

If the 11-year modulation cycle is due to an 11-year cycle in the emission of such propagating regions, as suggested in the references above and by Perko & Fisk [1983], then how would the phase of the 11-year modulation propagate? Venkatesan et. al. [1984] have remarked that "an unexpected result of [our] study is the apparent simultaneity (to within one solar rotation) of the occurrence of solar minimum at [1 and] 10 AU." This implies a phase speed of >700 km/s, which is distinctly faster than the 500 km/s of the observed episodic decreases. We show in this paper that the simplest episodic model of modulation predicts that the phase speed of the 11-year modulation moves outward at up to twice the speed of the

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individual intensity decreases.

2. Heuristic Model. We consider propagating, episodic modulation in a quasi-steady, "Force-field" model [Gleeson & Axford, 1968]. The modulation parameter is defined as

$$\Phi(r,t) = \int_r^R V\, dr'/K(r',t)$$

where "V" is the solar wind speed and "K(r',t)" is the radial diffusion coefficient for the cosmic rays. Since 1/K is proportional to the amount of turbulence, and regions of turbulence propagate at speed V,

$$\Phi(r,t) = \int_r^R V\, dr'/K(0,t-r'/V)$$

$\Phi$ then varies with the solar cycle because of the changing rate of emission from the Sun of scattering regions which propagate outward at speed V to a boundary at R, where their effect ceases.

A scattering region emitted from the Sun at time $t_0$ causes a cosmic-ray decrease to begin at radius $r_1$ when the region passes at time $t_1=t_0+r_1/V$. At $r_2>r_1$, it begins at $t_2=t_0+r_2/V$. The end of the effect at both $r_1$ and $r_2$ occurs near the time $t_E=t_0+R/V$ when the region leaves the modulating sphere at radius R. For various reasons, the end is not clearly seen in observations. Still, the middle of the lasting effect on modulation at $r_1$ occurs at time $t_{m1}=(t_1+t_E)/2=t_0+(r_1+R)/2V$, and likewise at $r_2$, $t_{m2}=t_0+(r_2+R)/2V$. Thus, because the beginning of the effect travels at speed V, but the end of it occurs at the same time everywhere, the overall lasting effect of each scattering region propagates at speed 2V.

Alternatively, the solar cycle can be modelled by varying the averaged level of turbulence in the solar wind and propagating it outward. Then the modulation parameter $\Phi(r,t)$ is the integral from r to R of V/K at the Sun at time (t-r'/V). If V/K varies as $\cos(\omega t)$ at the Sun, then $\Phi$ varies with time as $\cos[\omega(t-(R+r)/2V)]$. Again, this shows that the phase velocity of the variation in modulation is 2V.

3. Numerical Results. Perko & Fisk [1983] modelled an 11-year cycle in modulation based on episodic events. They assumed the Sun emits spherically-symmetric regions in which scattering is enhanced by a maximum factor of 10 over a band 2 AU wide. The regions travel outward at a speed of 400 km/s until they reach a boundary at 100 AU, where they disappear. The rate of emission was made to vary from one every 4 months at solar minimum to one every 2 weeks at solar maximum. The recovery phase of the cycle was modelled by reversing that behavior. The diffusion coefficient in the undisturbed solar wind (outside the discrete scattering regions) was set at

$$K = 4.3\beta(2 + P^2)\ 10^{21}\ cm^2/s$$

where "β" is the ratio of particle speed to the speed of light and "P" is particle rigidity. For boundary conditions and other details of the calculation, see Perko & Fisk [1983]. The result (Fig. 1) of their numerical integration of the time-dependent transport equations reproduces many of the features of the 11-year modulation. In particular, the episodic decreases propagate at the same speed as the scattering regions (see solid bar at the base of Fig. 1, which shows the propagation time of a scattering region and its accompanying intensity decrease going from 1 to 30 AU). The general level of modulation increases as the rate of emission of these regions increases; but as the rate decreases, the total number of regions in the heliosphere goes down, and there is a cosmic-ray minimum and recovery.

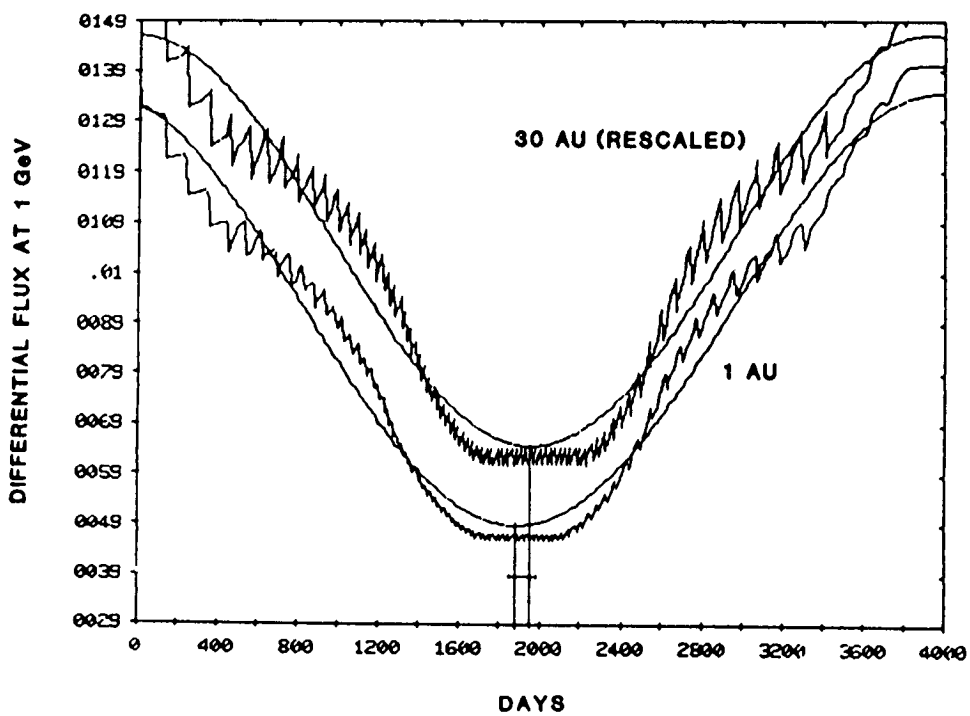


Fig. 1. Numerical calculation of flux (arbitrary units) of 1-GeV protons over the solar cycle, from one sunspot minimum to the next, at 1 and 30 AU. Individual decreases in intensity propagate from 1 to 30 AU in 125 days, shown by the bar at the base of the figure, but the time delay between cosmic-ray minima is only 68 days, shown by the vertical lines.

The smooth curves superposed on the numerical results are sine functions fitted to the results by a least-squares algorithm. The fitted parameters of the sine curves yielded the times of cosmic-ray minimum at 1 and 30 AU. These are indicated by the vertical lines connecting the curves with the abscissa.

It is a remarkable new result that the cosmic-ray minimum at 30 AU shown in Figure 1 occurred only 68 days after the minimum at 1 AU, which implies a propagation speed of 740 km/s, 1.85 times faster than the 400 km/s speed of individual decreases.

4. Conclusions. This simple model demonstrates that the phase of the 11-year cosmic-ray cycle, including recovery, propagates outward even under the simplified assumption of spherical symmetry. This outward propagation may not, therefore, be considered as a signature of models that allow preferential access to the solar cavity via the polar regions. Furthermore, this modulation phase moves at approximately twice the solar wind speed because the flux at a given radius depends on the average state of the heliosphere in the region between this radius and the outer boundary.

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